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Probing double parton scattering with leptonic final states at the LHC¹

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We discuss the prospects of observing double parton scattering (DPS) processes with purely leptonic final states at the LHC. We first study same-sign $W^\pm W^\pm$ pair production, which is particularly suited for studying momentum and valence number conservation effects, followed by discussions on double Drell–Yan and production of J/ψ pairs. The effects of initial state and intrinsic transverse momentum smearing on pair-wise transverse momentum balance characteristic to DPS are studied quantitatively. We also present a new technique, based on rapidity differences, to extract the DPS component from a double J/ψ sample recently studied at the LHCb.

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1 Introduction

Due to the composite nature of hadrons, it is possible to have multiple parton hard-scatterings, i.e. events in which two or more distinct hard parton interactions occur simultaneously, in a single hadron-hadron collision. For a given invariant mass, such cross sections tend to increase with collision energy due to the rapidly increasing parton fluxes when successively lower momentum fraction x is being probed. The high collision energies at the LHC thus provides a valuable opportunity to observe multiple parton hard-scatterings. In particular, many double parton scattering (DPS) processes involving leptonic final states could become accessible for the first time. These include double electroweak processes, for example production of same-sign W pairs ($W^\pm W^\pm$) and double Drell-Yan (DDY) interaction, and also pair production of J/ψ 's. Compared with the DPS processes already observed, namely final states involving 4 jets (at the AFS collaboration at the CERN ISR [1]), and $\gamma + 3$ jets (at the CDF [2] and the D0 [3] collaborations at the Fermilab Tevatron), properties of the leptonic final states can be measured much more precisely. These processes also involve different scales and initial state partons, and hence provide complementary information on the non-perturbative structure of the proton to the information derived from other DPS reactions. It is therefore important to study properties and prospects for observing various DPS processes in detail.

The general expression for the DPS cross section $\sigma_{(A,B)}^{DPS}$ is given by

$$\begin{aligned} \sigma_{(A,B)}^{DPS} = & \frac{m}{2} \sum_{i,j,k,l} \int dx_1 dx_2 dx'_1 dx'_2 d^2b \\ & \times \Gamma_{ij}(x_1, x_2, b; t_1, t_2) \Gamma_{kl}(x'_1, x'_2, b; t_1, t_2) \hat{\sigma}_{ik}^A(x_1, x'_1) \hat{\sigma}_{jl}^B(x_2, x'_2), \end{aligned} \quad (1)$$

where $\Gamma_{ij}(x_1, x_2, b; t_1, t_2)$ is the generalised double parton distribution function for partons i, j with momentum fractions x_1, x_2 at scales $t_1 \equiv \ln(Q_1^2)$, $t_2 \equiv \ln(Q_2^2)$. The two partons are separated by a transverse distance b . The scales t_1 and t_2 are equal to the characteristic scales of subprocesses A and B respectively. The quantity m is a symmetry factor that equals 1 if $A = B$ and 2 otherwise.

For processes that probe small x values, different partons may be expected to scatter independently to a good approximation. In this limit, we have

$$\Gamma_{ij}(x_1, x_2, b) = D_{ij}(x_1, x_2) F(b), \quad (2)$$

$$D_{ij}(x_1, x_2) = D_i(x_1) D_j(x_2), \quad (3)$$

where the scales are implicitly set to equal values ($t_1 = t_2$). The first expression factorises Γ_{ij} into a longitudinal double parton distribution (dPDFs) D_{ij} and a (flavour-independent) transverse distribution $F(b)$. In the second expression, D_{ij} is further

factorised into two single parton distribution functions D_i and D_j . Using these assumptions, $\sigma_{(A,B)}^{DPS}$ can be written as

$$\sigma_{(A,B)}^{DPS} = \frac{m}{2} \frac{\sigma_A \sigma_B}{\sigma_{\text{eff}}}, \quad \sigma_{\text{eff}} = \left[\int d^2b (F(b))^2 \right]^{-1}. \quad (4)$$

The quantity σ_{eff} is expected to be energy and process dependent, and is one of the DPS properties that requires a more precise experimental measurement.* Basic sum rule constraints, namely momentum and valence number conservation, may be included via the longitudinal dPDFs D_{ij} and could be probed in particular processes. In the following, we discuss the prospects of obtaining this information from the $W^\pm W^\pm$, DDY and double J/ψ processes at the LHC. The discussion is based on Refs. [4, 5, 6]. We refer readers to other contributions to these proceedings for phenomenological studies involving jets and recent theoretical and experimental developments.

2 Same-sign $W^\pm W^\pm$ pair production

It was first suggested in Ref. [7] that same-sign $W^\pm W^\pm$ process might be a clean channel for the observation of DPS. The irreducible background to the process, namely single parton scattering (SPS) production of a $W^\pm W^\pm$ pair must be accompanied by two additional partons in order to conserve electromagnetic charge. These extra partons provide excellent handles to separate the DPS signal from the SPS background.

It was subsequently pointed out in Refs. [6, 8] that in certain regions of final state phase space this process could be particularly sensitive to momentum and valence number constraints that must operate at some level on the two parton PDFs. The relevant region is the one in which both W s are produced in the *same* forward direction, since this configuration favours extraction of two large x (valence) quarks from one proton. Compared with simple factorised models, the sum rule constraints would suppress such configurations. The charged lepton η asymmetry

$$a_{\eta_l} \equiv \frac{\sigma(\eta_{l_1} \times \eta_{l_2} < 0) - \sigma(\eta_{l_1} \times \eta_{l_2} > 0)}{\sigma(\eta_{l_1} \times \eta_{l_2} < 0) + \sigma(\eta_{l_1} \times \eta_{l_2} > 0)}, \quad (5)$$

where η_{l_i} are the lepton pseudo-rapidities, should hence be positive for $|\eta_{l_1}|, |\eta_{l_2}| > \eta_l^{\text{min}}$ for some minimum pseudo-rapidity cut η_l^{min} , and should also increase with η_l^{min} .

The functional dependence of a_{η_l} on η_l^{min} is plotted in Figure 1, assuming that proton-proton DPS can be described in terms of dPDFs and taking various different forms for the dPDFs. The predictions from the GS09 dPDFs [8] in which momentum

*For concreteness, in the following numerical studies we shall use $\sigma_{\text{eff}} = 14.5$ mb, the value obtained by the CDF experiment[2].

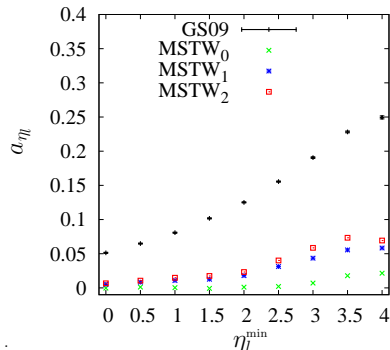


Figure 1: Charged lepton pseudo-rapidity asymmetry as a function of η_l^{\min} , the minimum lepton η cut, for positively-charged leptons from DPS in pp collisions at $\sqrt{s} = 14$ TeV, evaluated using different dPDF models.

Cuts	14 TeV LHC	$\sigma_{\mu^+\mu^+}$ [fb]	$\sigma_{\mu^-\mu^-}$ [fb]
$ \eta_l < 2.5$	$W^\pm W^\pm$ (DPS)	0.82	0.46
$20 \leq p_T^l \leq 60$ GeV	$W^\pm Z/\gamma^*$	5.1	3.6
$\cancel{E}_T \geq 20$ GeV	$Z/\gamma^* Z/\gamma^*$	0.84	0.67
OS lepton veto	$b\bar{b}$ ($p_T^b \geq 20$ GeV)	0.43	0.43

Table 1: Selected cuts (left) on the same-sign muons, and cross sections [fb] (right) after cuts for signal and background same-sign W production, including branching ratio into muon.

and valence number constraints are implemented, are compared with those from simple “MSTW $_n$ ” sets, defined as $D_{ij}(x_1, x_2) = D_i(x_1)D_j(x_2)\theta(1-x_1-x_2)(1-x_1-x_2)^n$ for $n = 0, 1, 2$, in which momentum constraints are implemented very crudely and valence number constraints are not included at all. It is known that there are theoretical problems in describing DPS using dPDFs (see e.g. [9]) and none of the dPDF sets used take account of the potential contributions to DPS starting from 2 or 3 nonperturbative partons in a correct way. However, such contributions play a subdominant role in determining the shape of $a_{\eta_l}(\eta_l^{\min})$, and the main force shaping this distribution is in fact the inclusion of basic momentum and number sum rule constraints, which are contained at least in an approximate way in GS09.

To see how well the DPS $W^\pm W^\pm$ signal can be extracted from background, we perform a parton level study, relevant for the general purpose detectors ATLAS and CMS, to look for same-sign muon pairs. We include diboson ($W^\pm Z/\gamma^*, Z/\gamma^* Z/\gamma^*$), heavy flavour ($b\bar{b}$) production as well as the irreducible $W^\pm W^\pm + j$ ’s SPS background discussed above.[†] The cuts and resulting cross sections are displayed in Table 1. We

[†]We refer readers to the original paper [6] for a technical account of the simulation.

Cuts	DDY cross sections [fb] at LHCb	
	DPS	SPS
$1.9 < \eta < 4.9, \quad p_T > 1 \text{ GeV}$		
$m_{\mu^+\mu^-} > 4 \text{ GeV}$	7 TeV	0.08
$9.2 < m_{\mu^+\mu^-} < 10.5 \text{ GeV veto}$	14 TeV	0.16
$m_{4\mu} < 40 \text{ GeV veto}$		0.68

Table 2: Cuts (left) and DPS and SPS DDY cross sections [fb] (right) for pp collisions at 7 and 14 TeV.

see that a small excess can be expected, with the background dominated by diboson production. There are however additional handles which can help distinguish the signal from background. See Ref. [6] for more details.

3 DDY and double J/ψ at LHCb

One of the main characteristic in DPS is the so-called pair-wise balancing, in which the final states from the two hard scattering processes have zero transverse momentum at parton level. This has been used to help identify the presence of double parton scattering in previous experiments. If all four DPS final states are charged leptons, in principle pair-wise balancing could also be observed.

In the following, we focus on events with four muon final states, forming two opposite sign (OS) muon pairs. We look in the low invariant mass region, where the DPS to SPS ratio is expected to be larger. LHCb has excellent low p_T muon acceptance, which can go down to $\sim 1 \text{ GeV}$, and muon identification in the low mass region, making it well suited for studying 4-muon DPS events. In the low mass region, the factorisation into two single 2-to-2 hard scatterings in Eq. 4 is likely to be a good approximation, and so is used in the numerical analysis that follows.

We first discuss DDY. We use **Herwig++ v2.4.2** [10] to generate the DPS signal, and **MADGRAPH v5.1.2.4** [11] to generate the SPS 4-muon background, which is then interfaced to **Herwig++** for parton showering. We also include a Gaussian intrinsic p_T smearing, parameterised by the parameter $\sigma = 2 \text{ GeV}$, to provide a more realistic simulation. The cuts and the resulting cross sections are displayed in Table 2. We see that while at 7 TeV, the cross section is too low for an expected integrated luminosity of $\mathcal{O}(1) \text{ fb}^{-1}$, it might be possible to observe DPS events at the 14 TeV LHC at high luminosity.

In principle, the DPS signal and SPS background can further be distinguished by pair-wise balancing. However at low invariant mass, the presence of initial state radiation (ISR) and intrinsic p_T smearing significantly affect the balancing property. Due to the ambiguity in grouping the 4 muons into 2 OS pairs, a pair-wise balancing

variable (S)

$$S = \frac{1}{2} \left(\frac{|\mathbf{p}_{T\mu_1^+} + \mathbf{p}_{T\mu_1^-}|}{p_{T\mu_1^+} + p_{T\mu_1^-}} + \frac{|\mathbf{p}_{T\mu_2^+} + \mathbf{p}_{T\mu_2^-}|}{p_{T\mu_2^+} + p_{T\mu_2^-}} \right), \quad (6)$$

is used to group the muons into 2 OS pairs by minimising S . The S distributions including different radiation effects are displayed in Figure 2 (left plot). Clearly, these distributions depend sensitively on the radiation effects, with the SPS and DPS distributions becoming more similar after these effects are included.

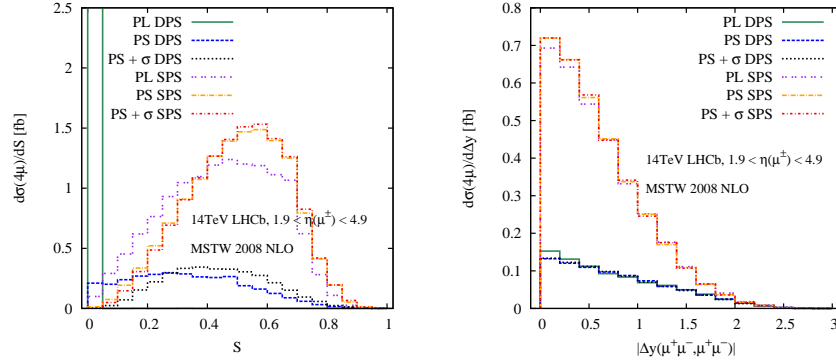


Figure 2: Distributions of the pair-wise balancing variable S (left) and the rapidity difference $|\Delta y(\mu^+\mu^-, \mu^+\mu^-)|$ (right) for the DPS and SPS processes including different radiation effects. In the figure, PL stands for “parton level”, PS stands for “parton shower”, and σ indicates the inclusion of intrinsic p_T smearing.

On the other hand, longitudinal kinematic variables are expected to be less sensitive to the radiation effects, which primarily affects kinematic distributions on the transverse plane. One such variable is the rapidity difference $|\Delta y(\mu^+\mu^-, \mu^+\mu^-)|$ between the two OS muon pairs specified by minimising S , which has the additional advantage of being invariant under longitudinal boost. The distributions of $|\Delta y(\mu^+\mu^-, \mu^+\mu^-)|$ are displayed in Figure 2 (right plot). We see that both the DPS and SPS distributions are much more stable against ISR and intrinsic p_T smearing. Also, the fraction of DPS events increases with $|\Delta y(\mu^+\mu^-, \mu^+\mu^-)|$, making it an excellent variable to distinguish DPS from SPS events.

The above observations can be applied to double J/ψ production. Compared with DDY, this process benefits from the large *single* J/ψ cross section, while the theoretical description of the production is an active area of current research. In double J/ψ production there is no ambiguity in grouping the 4 muons into 2 OS pairs, as the correct pairing should have $\mu^+\mu^-$ invariant mass close to the physical J/ψ mass. The set of cuts and the resulting cross section is displayed in Table 3.

Cuts	Double J/ψ cross sections [pb] at LHCb	
$1.9 < \eta < 4.9$	DPS	SPS
$p_T > 1 \text{ GeV}$	7 TeV	1.70
$m_{\mu^+\mu^-} \simeq m_{J/\psi}$	14 TeV	2.62

Table 3: Cuts (left) and DPS and SPS double J/ψ cross sections [pb] (right) including $\mathcal{BR}(J/\psi \rightarrow \mu^+ \mu^-)$ for pp collisions at 7 and 14 TeV.

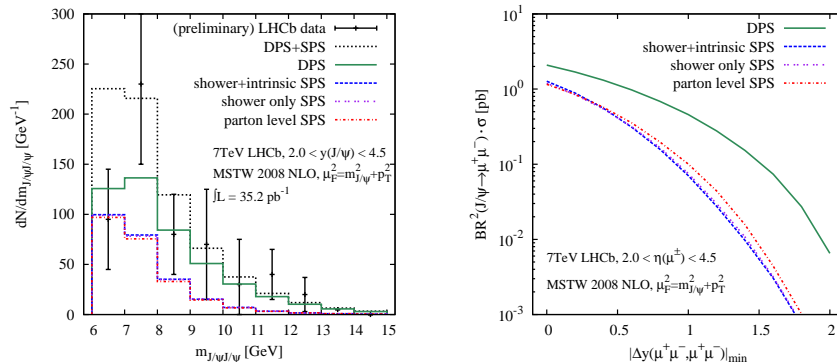


Figure 3: Distributions of invariant mass $m_{J/\psi J/\psi}$ (left) and variation of the cross section as a function of minimum rapidity difference $|\Delta y(\mu^+ \mu^-, \mu^+ \mu^-)|$ (right) for the DPS and SPS processes. Note that slightly different cuts, motivated by the cuts used in the recent LHCb measurement [12], have been used to obtain the above distributions, c.f. [4, 5].

In fact, recent results from LHCb [12] might already indicate the presence of double J/ψ events from DPS. Assuming $\sigma_{\text{eff}} = 14.5$ mb, the theoretical cross sections for the SPS and DPS double J/ψ processes are similar. However the $m_{J/\psi J/\psi}$ invariant mass distribution is different, with the DPS distribution peaking at slightly higher values. In Figure 3 (left plot), we show that combining contributions from DPS and SPS might provide a better fit to data.

The large double J/ψ cross section allows extraction of the DPS events from the SPS background by imposing a cut on minimal $|\Delta y(\mu^+\mu^-, \mu^+\mu^-)|$. In Figure 3 (right plot), we show the variation of cross section as a function of $\min |\Delta y(\mu^+\mu^-, \mu^+\mu^-)|$. Increasing $\min |\Delta y(\mu^+\mu^-, \mu^+\mu^-)|$ can result in much higher DPS fractions. With more upcoming LHC data, this could be an excellent tool in establishing the presence of DPS double J/ψ events [5].

4 Summary

Measurements undertaken at the LHC will be crucial for improving the theoretical description of multiple parton scattering, in particular double parton scattering. We have studied the prospects of observing DPS with leptonic final states. Both

same-sign $W^\pm W^\pm$ and Drell–Yan pair production can be considered standard candle processes at hadron colliders, as the leptonic final states provide clean experimental signatures, while the theoretical predictions of the 2-to-2 subprocesses are under control. The cross sections for these processes are of $\mathcal{O}(0.1)$ fb, and so will require high luminosities to obtain unambiguous signals. On the other hand, double J/ψ production has a much larger cross section, and a significant DPS component may already be present in a recent LHCb study. With more data in the 7 TeV run, the DPS component can be disentangled from the SPS component using the rapidity separation between the two reconstructed J/ψ 's.

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